State of Wisconsin
Department of Transportation

Facilities Development Manual

ORIGINATOR Director, Bureau of Highway Development	PROCEDURE 13-10-10

CHAPTER 13	Drainage
SECTION 10	Hydrology
SUBJECT 10	Hydrograph Development and Routing

Development

A hydrograph is defined as the graph of flow (rate versus time) at a stream section. The four basic hydrograph types are:

1. Natural Hydrographs: Obtained directly from the flow records of a gaged stream.
2. Synthetic Hydrographs: Obtained by using watershed parameters and storm characteristics to simulate a natural hydrograph.
3. Unit Hydrographs: A natural or synthetic hydrograph for one inch of direct runoff. The runoff occurs uniformly over the watershed in a specified time.
4. Dimensionless Hydrographs: Made to represent many unit hydrographs by using the time to peak and the peak rates as basic units and plotting the hydrographs in ratios of these units. Also called the "Index Hydrograph."

Hydrographs are used in the planning and design of water control structures, especially detention basins, which are used to minimize downstream flooding by attenuating the peak flows of storms with specific duration frequencies. They are also used to show the hydrologic effects of existing or proposed projects.

The urbanization of rural areas increases peak flows, which has and will continue to overtax existing downstream structures such as highway drainage facilities. Replacing such overtaxed facilities with larger or additional structures is one option, but designers should also investigate adding a detention basin(s) upstream of the problem structure.

For both large and small watersheds, the hydrograph development methods discussed in this section are:

1. HEC-1
2. The Natural Resources Conservation Service (NRCS) Tabular Method, TR55
3. The Unit Hydrograph Method
4. The NRCS Triangular Dimensionless Unit Hydrograph Method
5. The NRCS Curvilinear Dimensionless Unit Hydrograph Method

These methods can be easily applied through manual computations to small watersheds, but not large watersheds, hence, it is necessary to use a computer program in these cases. The computer program selected for inclusion here is the NRCS TR-55, "Urban Hydrology for Small Watersheds" which makes use of the NRCS curvilinear unit hydrograph.

HEC-1

HEC-1 was developed by the U.S. Army Corps of Engineers, Hydraulic Engineering Center. It is designed to simulate surface runoff from various duration storms over a watershed. The conversion of precipitation to direct runoff can be simulated by HEC-1 for both small or large watersheds. Hydrograph combining, channel and reservoir routing and sub-basin runoff are some of the basic components that HEC-1 uses for a simple or complex watershed study.

The HEC-1 computer package has the following capabilities:

1. Simulates watershed runoff and stream flow from design or historical rainfall.
2. Uses unit hydrograph, loss rate and stream flow routing procedures from measured data.
3. Simulates reservoir and channelization flood controls.

NRCS Tabular Method, TR-55

The Tabular Method is an approximation of the more detailed hydrograph analysis contained in Section 4-Hydrology of the NEH-4 (4). Composite hydrographs can be developed for any point within a watershed by dividing the watershed into subareas, developing simple hydrographs for each subarea, routing the simple hydrographs to the point in question, and adding the routed simple hydrographs. The factors required to determine these hydrographs are:

- 24-hour rainfall amount,
- a given rainfall distribution (Type II in Wisconsin),
- hydrologic soil cover complexes (runoff numbers),
- time of concentration,
- travel time, and
- drainage area.

This method should not be used when the runoff curve numbers of the subareas vary appreciably and when runoff volumes are less than 1.5 inches for curve numbers less than 60. Moreover, for most watershed conditions (urban or rural), this procedure can be used to determine hydrographs for subareas up to approximately 2000 acres **(809 ha)**.

For a thorough discussion of the Tabular Method, with an accompanying example problem, see routing section.

Unit Hydrograph

The unit hydrograph is a very important tool for estimating runoff amounts for various frequencies that may occur at a specific point of a stream. The use of this method requires continuous records of runoff and precipitation for the specific drainage basin.

Sherman(6) defined the unit hydrograph as a hydrograph with a one-inch volume of runoff from a rainstorm of specified duration, time-intensity pattern, and areal pattern. Increasing the duration of the rainfall increases the unit hydrograph time base and peak, because the unit hydrograph contains only one inch of runoff.

In practice, unit hydrographs are generally based on an assumption of uniform intensity of rainfall. Usually the Unit Hydrograph Method is applied to basins small enough so that the areal pattern is rather uniform. The acceptable drainage basin size is equal to or less than 200 square miles **(518 km^2)**.

Theoretically, a given drainage basin will exhibit an infinite number of unit hydrographs, one for every possible duration of rainfall, every possible time-intensity pattern, and every possible areal pattern. In design practice, only the duration of the rainfall is allowed to vary, while variations in areal patterns are ignored. Moreover, unit hydrographs are developed from rainstorms that exhibit basically a rainfall pattern of uniform intensity. Short-duration unit hydrographs can be used to develop a unit hydrograph resulting from a long rain of varying intensity.

Procedure

The basic steps in the development of a unit hydrograph are:

1. Analyze the stream-flow hydrograph separating the surface runoff from the groundwater flow.
2. Determine the total volume of direct runoff from the storm that produced the original hydrograph. This volume is equal to the area under the original hydrograph minus the groundwater flow area.
3. Divide each ordinate of the direct runoff hydrograph by the total direct runoff volume in inches. The unit hydrograph is the plot of these answers against time.
4. Finally, determine the effective duration of the rainfall that produced this unit hydrograph. This can be obtained by studying the hyetograph of the rainfall.

Generally, the hydrograph for a given drainage basin for a specified design storm (duration, effective rainfall, or total runoff) may be constructed by multiplying each ordinate of the specified duration unit hydrograph by the total runoff (inches).

NRCS Triangular & Curvilinear Dimensionless Unit Hydrograph Methods

Basically, the Triangular and Curvilinear Methods are the same, except the Triangular Method, as its name implies, substitutes a dimensionless unit hydrograph for the more accurate curvilinear dimensionless unit hydrograph. This method develops synthetic hydrographs for a specific watershed by using watershed parameters, storm characteristics, and a dimensionless unit hydrograph. The dimensionless unit hydrograph was developed from a large number of natural unit hydrographs from watersheds varying widely in size and geographical location.

The shape of the dimensionless unit hydrograph is determined by the drainage area and time of concentration, hence, the watershed should be divided into hydrologic units of uniformly shaped areas. If possible, these subareas should be less than 20 square miles **(52 km^2)** and exhibit a homogeneous drainage pattern.

The basic data required to develop synthetic hydrographs are:

1. Twenty-four-hour and/or six-hour rainfall amount for a specific rainfall frequency
2. Rainfall distribution
3. Hydrologic soil cover complexes (runoff numbers)
4. Times of concentration for the subareas
5. Travel times through reaches
6. Drainage areas for each sub-area

For a thorough discussion of this method, with accompanying example problems, see Chapter 16 of NEH-4 (4). In addition, these synthetic hydrographs can also be generated by computer through the use of version 2.1 of NRCS-TR-55 (5).

Routing

Hydrograph development and hydrograph routing are closely interrelated. A simple hydrograph for a subarea of a watershed can and is developed without routing, but the downstream, more complex hydrographs must be developed through routing and/or combining the simple upstream hydrographs.

In the American Society of Civil Engineers Manual, "Nomenclature for Hydraulics," flood routing is variously defined as follows:

"routing (hydraulics).--(1) The derivation of an outflow hydrograph of a stream from known values of upstream inflow. The procedure utilizes wave velocity and the storage equation; sometimes both. (2) Computing the flood at a downstream point from the flood inflow at an upstream point, and taking channel storage into account.

"routing, flood.--The process of determining progressively the timing and shape of a flood wave at successive points along a river.

"routing, stream flow.--The procedure used to derive a downstream hydrograph from an upstream hydrograph, or tributary hydrographs, and from considerations of local inflow by solving the storage equation."

The purpose of flood routing is to mathematically determine from the inflow hydrograph the shape of the outflow hydrograph at specific locations in streams or structures during passages of floods. These outflow hydrographs are used in designing a water control structure or project.

Detention and retention basins have been used to control the effects and results of urbanization and urban runoff hydrology.

Urbanization Can Cause:

1. Reduction in natural storage capacity.
2. Increase in impervious area.
3. Greater direction and conveyance of runoff.

Urban Runoff Hydrology Results In:

1. Higher peak discharge (2 to 5 times).
2. Shorter time to peak, as high as 50 percent.
3. Higher velocity of storm runoff.
4. As much as 50 percent increased volume of storm runoff.
5. Reduction of infiltration, inflow and base stream flows.

To help alleviate these problems it may be necessary to design a retention/ detention facility. This facility may be designed as a pond, underground tank or parking lot as well as other types of facilities.

The following steps should be performed to assure a proper design.

1. Determine the purposes for which the basin will be used.
2. Determine the design storm inflow hydrographs before and after development.
3. Estimate the volume of storage needed.
4. Determine the depth-storage curve for the basin.
5. Select the outlet structure types compatible with the uses outlined in step 1 and determine the depth- outflow curve.
6. Determine the routing curve.
7. Perform the routing.
8. Add additional outlet features to ensure that the peak outflow rate is reduced to at least the pre-development rate for the more frequent storms.
9. Perform the routings for these smaller storms to ensure compliance.
10. Check the length of time needed to empty the basin for the various storms to determine if the other uses of the basin will be unduly delayed and/or if water quality detention times are met.

For the example shown in this procedure, a detention pond (122' x 122') will be designed.

Note: the NRCS publication (reference 5) is needed to fully understand the following example.

Detention Pond Example

(NRCS TR-55 Tabular Hydrograph Method)

Given:

1. Area of Watershed = 10 Acres
2. Curve Number = 75 *****
3. 50 Year 24 hour Rainfall = 5" *****
4. Time of Concentration (t_c)=18 minutes *****
5. Type II Rainfall Distribution *****
6. Maximum Post Q £ Pre Q of 8 cfs.

***** Items 2 - 5 can be determined by using Chapters 2 and 3 of NRCS. TR-55(5) and associated exhibits and figures.

Procedure

The procedure shown below is based on the steps described above.

1. The basin is to be used as a detention pond.
2. Determine storm inflow hydrograph:
   A. Determine runoff from Table 2-1, NRCS TR-55 (5).
      Rainfall = 5"
      CN = 75
      Runoff = 2.45"
   B. Complete work sheet (Figure 1B)
   C. Complete work sheet (Figure 2B) using a Type II rainfall distribution to develop a hydrograph. See reference 5. The NRCS TR-55 computer program (version 2.1 non-Windows) may be used instead of manually calculating the results of steps A - C.
   D. Plot the tabulated hydrograph. See Figure 3.
3. Determine volume of storage required to detain a 50 year storm with Q = 8 cfs.
   Required storage can be determined by assuming an outflow curve (see reference 5 and Figure 3 for details) and determining the area between the inflow curve and the outflow curve. For this example, using a planimeter on the area between the curves in Figure 3 yields a required volume of approximately 54,000 ft^3.
4. Depth Storage Relationship:
   We will first evaluate a trapezoidal storage pond with the following dimensions. (see Figure 11)
   Square, L = W = 122 ft. (bottom of pond)
   Side slope (Z) = 4:1

The equation below can be used to find the volume of a trapezoidal pond. Use it to determine the depth needed to provide adequate storage for the detention pond.

Volume = $LWD + (L + W) ZD^2 + 4/3\, Z^2D^3$	
Depth	Volume
0.5	7688
1.0	15881
1.5	24594
2.0	333842
2.5	43643
3.0	54011
3.5	64963

From this table a depth of 3.5 ft is chosen to provide ample storage plus some freeboard. See Figure 8 for a plot of this data. This is the depth-storage relationship.

5. Determine outlet pipe size by using Figure 4, with concrete pipe/grooved end with head wall, determine pipe size that can handle 8 cfs w/3.5 ft of head.
   For Figure 4, use a 12" concrete pipe with a grooved end with head wall.
6. The depth/outflow relationship can be determined by multiple applications of Figure 4 with a constant pipe diameter (D) of 1 ft. See the table below.

Depth (ft)	HW/D (ft)	Outflow (cfs)
.5	.5	.75
1.0	1.0	2.5
1.5	1.5	4.0
2.0	2.0	5.4
2.5	2.5	6.3
3.0	3.0	7.2
3.5	3.5	8.0

Plot the information as shown on Figure 5.

7. Construct a storage indicator table, Figure 6B, plot column 2 vs column 6 to create a storage indicator curve as shown on Figure 7. The curve is used to complete Figure 9B. When the storage indicator number (column 6 of Figure 9B) reaches a maximum, then peak discharge occurs.

Figure 10 shows the actual inflow and outflow hydrographs. The peak outflow is 5.49 cfs. Since the maximum Q post = 8 cfs, this solution is acceptable. Therefore, steps 8-10 of the process need not be done. If a design with a Q post closer to 8 cfs is desired then the problem should be re-examined.

REFERENCES

(1) Poertner, Herbert G., "Practices in Detention of Urban Storm Water Runoff," American Public Works Association, Special Report No. 43, 1974.

(2) Terstriep, Michael L., and Stall, John B., "Urban Runoff by Road Research Laboratory Method," Journal of the Hydraulics Division-ASCE, November 1969, pp. 1809-1834.

(3) Stall, J.B., and Terstriep, M.L., "Storm Sewer Design--An Evaluation of the RRL Method," prepared for the Office of Research and Monitoring of the USEPA, October 1972.

(4) U.S. Department of Agriculture, National Resources Conservation Service, National Engineering Handbook, Section 4, Hydrology (NEH-4), August 1972.

(5) National Resources Conservation Service, Engineering Division, "Urban Hydrology for Small Watersheds", Technical Release 55, June 1986

(6) Sherman, L.K., "Stream flow from Rainfall by the Unit-Graph Method," Eng. News-Rec., Volume 108, pp. 501-505, 1932.

★

Basin Watershed Data

Project ____________________ Location__________________________ By____________ Date___________

Circle One: Present Developed_____________ Frequency (yr) _______ Checked _________ Date _______

Subarea Name									
Drainage Area A_m (mi^2)									
Time of Concentration T_c (hr)									
Travel Time through subarea T_t (hr)									
Downstream Subarea names									
Travel time summation to outlet $\sum T_t$ (hr)									
24-hr Rainfall P (in.)									
Runoff Curve number CN									
Runoff Q (in.)									
A_mQ (mi^2 - in.)									
Initial abstration 1_a (in.)									
1_a /P									

Basin Watershed Data

Project *Detention Example* Location________________________ By *WisDOT* Date___________

Circle One: Present Developed___________ Frequency (yr) *50* Checked _________ Date _______

Subarea Name	**#1**								
Drainage Area A_m (mi^2)	**10 ACRE =.0156**								
Time of Concentration T_c (hr)	**.3**								
Travel Time through subarea T_t (hr)	**0**								
Downstream Subarea names	**--**								
Travel time summation to outlet $\sum T_t$ (hr)	**--**								
24-hr Rainfall P (in.)	**5**								
Runoff Curve number CN	**75**								
Runoff Q (in.)	**2.45**								
A_mQ (mi^2 - in.)	**.038**								
Initial abstration 1_a (in.)	**.667**								
1_a /P	**.1**								

Project ____________________ Location ________________________________ By ___________ Date ______________

Circle One Present Developed _______________________________ Frequency (yr) ________________ Date ______________

Subarea Name	Basic Watershed Data used *				Select and enter hydrography times in hours **												
	Sub-area T_c (hr)	$\sum T_t$ to oulet (hr)	$1_a/P$	A_mQ (mi2-in)													
					Discharge at selected hydrography time ** ---------(cfs)---------												
Composite hydrography at outlet																	

* From Figure 1

** Use rainfall distribution Type II for Wisconsin

*** Hydrography discharge for selected times is A_mQ multipled by tabular discharge.

Project _____***Detention Example***____ Location ________________________________ By___***WisDOT***__ Date ______________

Circle One Present Developed _______________________________ Frequency (yr) ___***50***___

Checked __________Date ___________

Subarea Name	Basic Watershed Data used *				Select and enter hydrography times in hours **												
	Sub-area T_c (hr)	$\sum T_t$ to oulet (hr)	$1_a/P$	A_mQ (mi2-in)	11.0	11.3	11.6	11.9	12.0	12.1	12.2	12.3	12.4	12.5	12.6	12.7	12.8
					Discharge at selected hydrography time ** (cfs)												
#1	.3	.0	.1	.038	.76	1.1	1.6	4.5	8.9	17	25.7	25.7	17.4	10.6	7.4	5.5	4.3
									HOURS								
#1	.3	0	.1	.038	13.0	13.2	13.4	13.6									
					3	2.5	2.2	1.9									
Composite hydrography at outlet																	

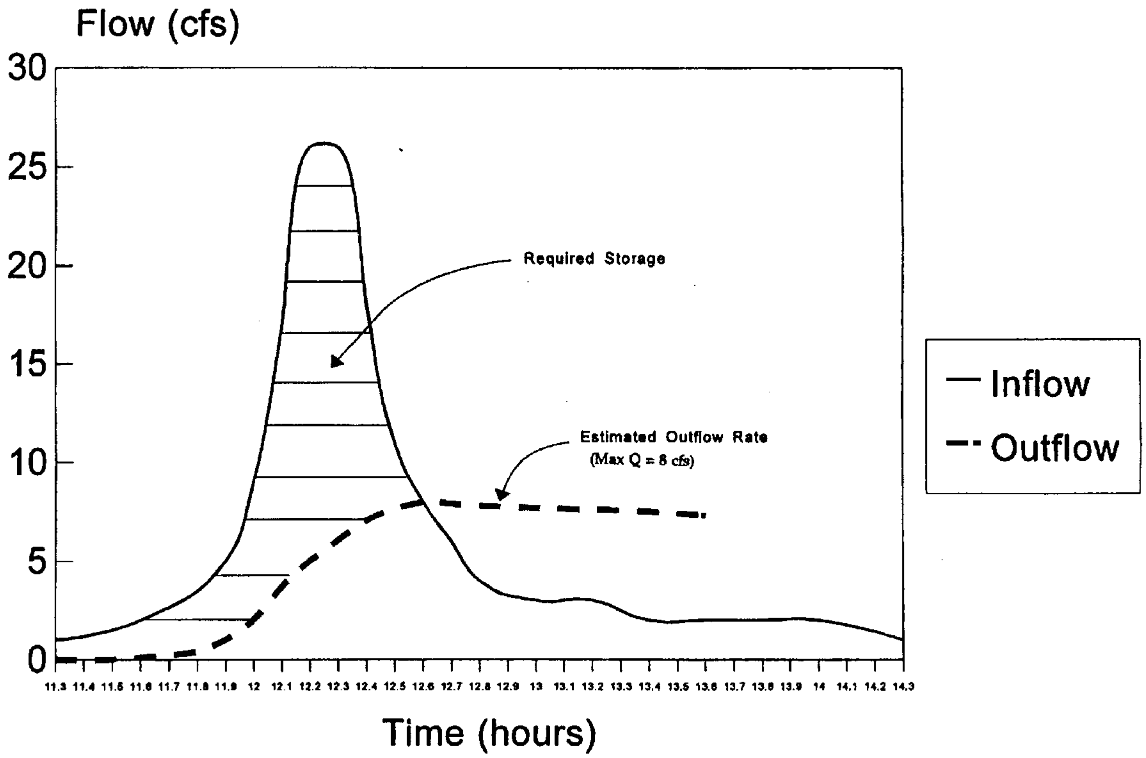
* From Figure 1

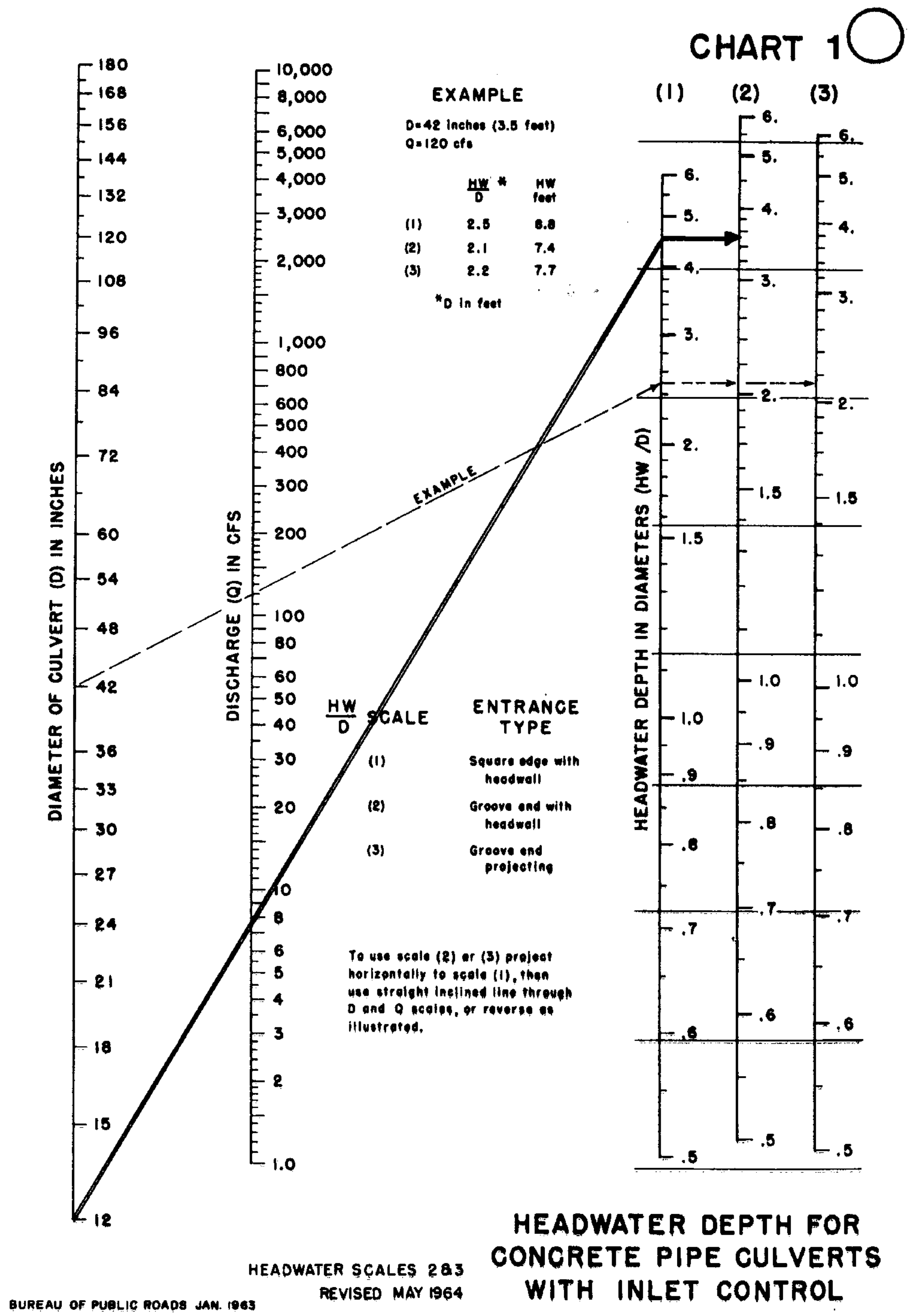
** Use rainfall distribution Type II for Wisconsin

*** Hydrography discharge for selected times is A_mQ multipled by tabular discharge.

Detention Example

50 year, 24hr storm





HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

181

Depth - Outflow

12" RCP

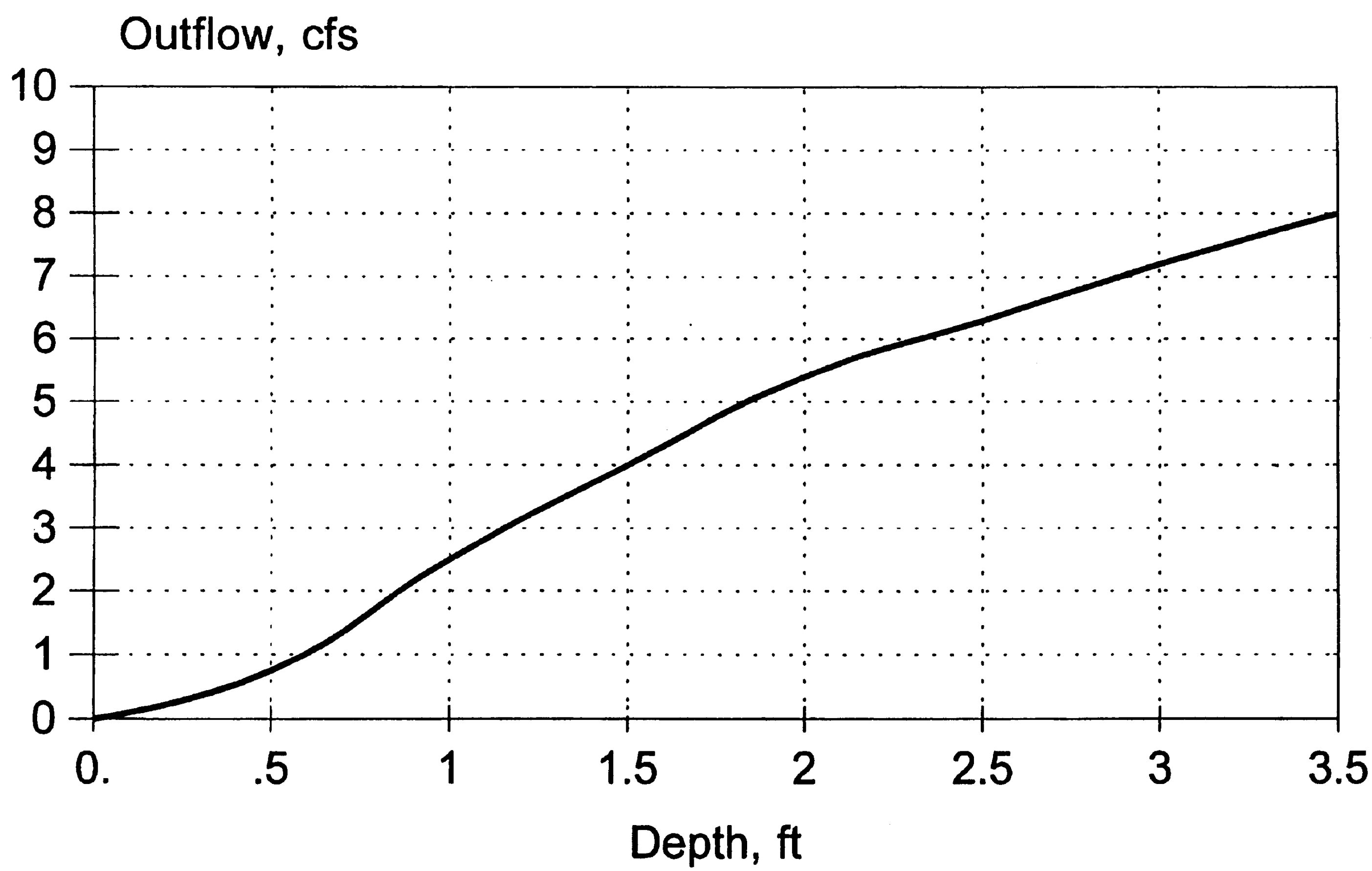


Table Number 1

Elevation (ft) (1)	Discharge (ft) (2)	Storage (ft^3) (3)	$\frac{0_2}{2}$ (4)	$\frac{S_2}{\Delta T}$ (5)	$\frac{S_2}{\Delta T} + \frac{0_2}{2}$ (6)

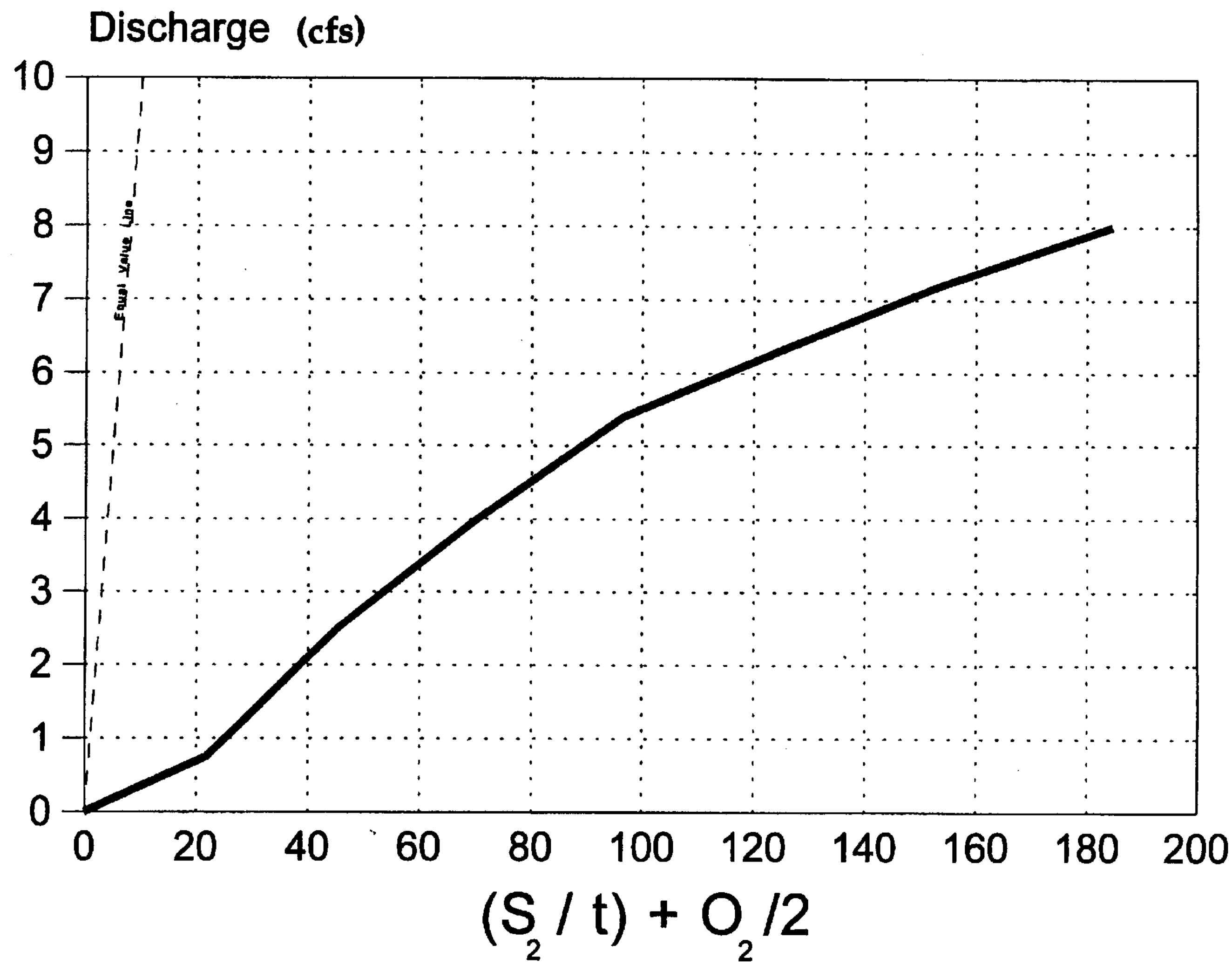
ΔT = 360 sec.

Table Number 1

Elevation (ft) (1)	Discharge (ft) (2)	Storage (ft^3) (3)	$\frac{0_2}{2}$ (4)	$\frac{S_2}{\Delta T}$ (5)	$\frac{S_2}{\Delta T} + \frac{0_2}{2}$ (6)
0.0	**0.0**	**0.0**	**0**	**0**	**0**
0.5	**.75**	**7688**	**0.38**	**21.4**	**21.78**
1.0	**2.5**	**15881**	**1.25**	**44.1**	**45.35**
1.5	**4.0**	**24594**	**2.0**	**68.3**	**70.3**
2.0	**5.4**	**33842**	**2.7**	**94**	**96.7**
2.5	**6.3**	**43643**	**3.15**	**121.2**	**124.35**
3.0	**7.2**	**54011**	**3.6**	**150.0**	**153.6**
3.5	**8.0**	**64963**	**4.0**	**180.5**	**184.5**

ΔT = 360 sec.

Storage - Indicator Curve



Stage - Storage Curve

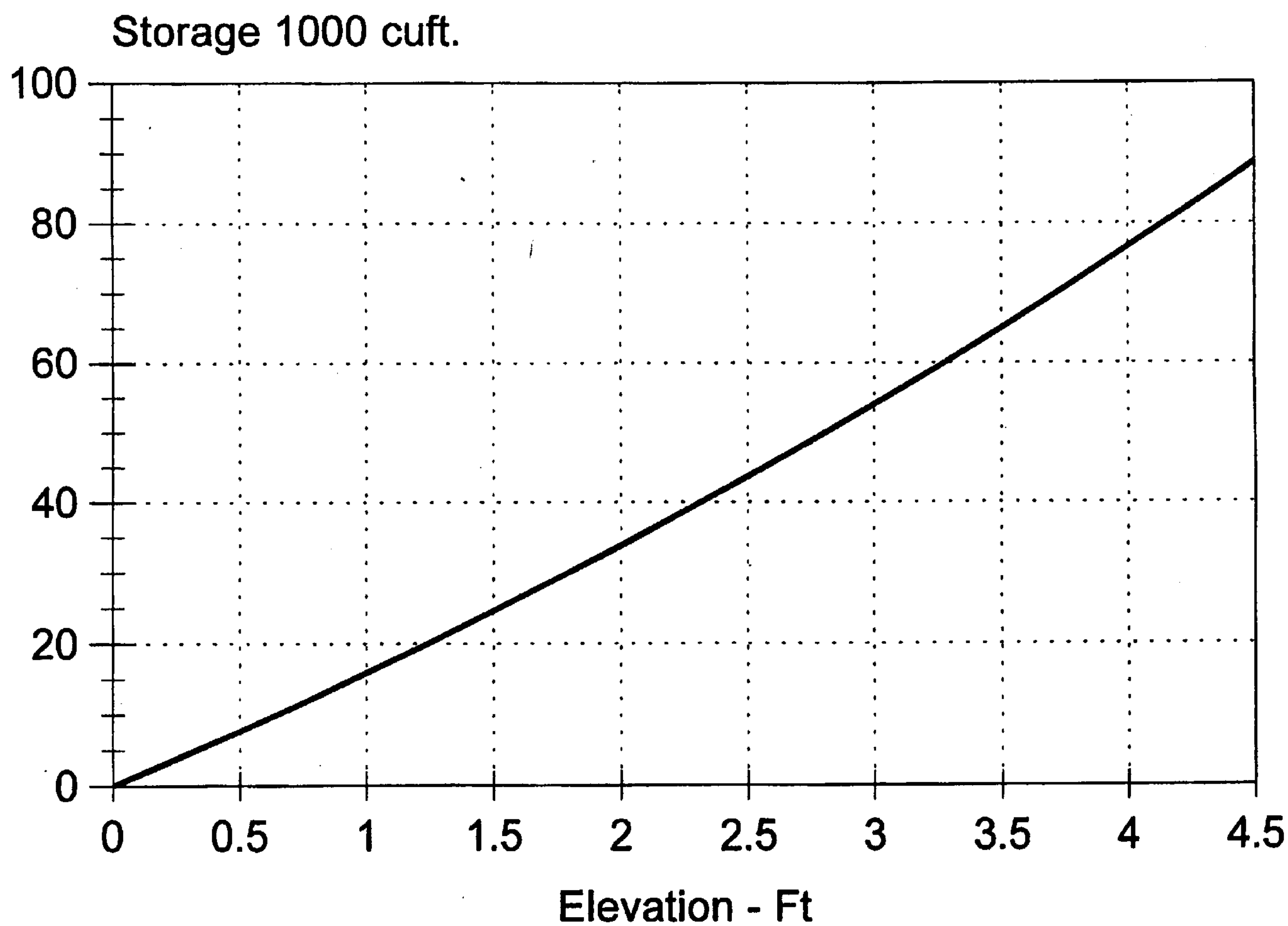


Table Number 2

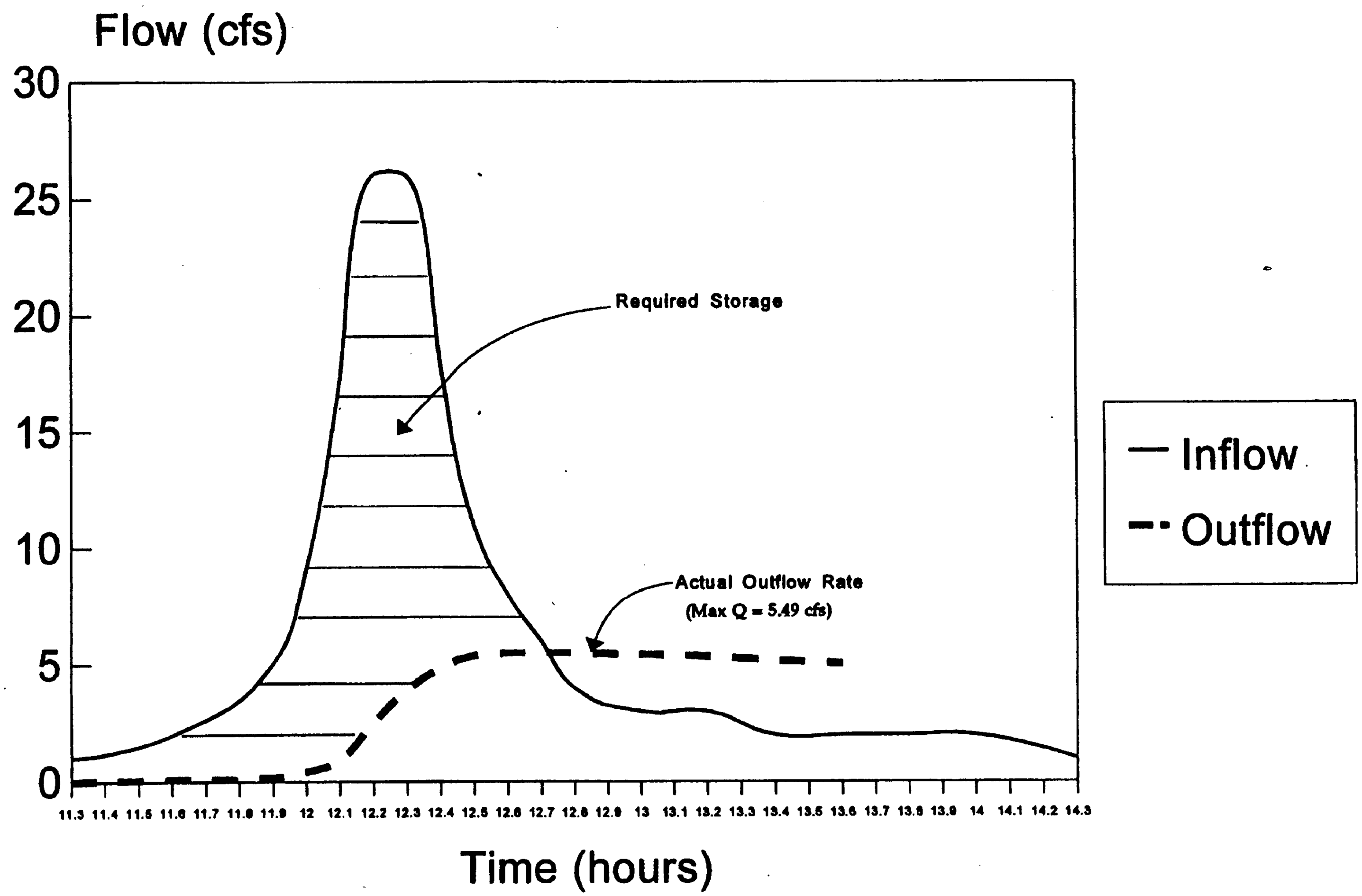
Time (hrs) (1)	Inflow (cfs) (2)	$\frac{I_1 + I_2}{2}$ (3)	$\frac{S_1}{\Delta T} + \frac{O_1}{2}$ (4)	O_1 (cfs) (5)	$\frac{S_2}{\Delta T} + \frac{O_2}{2}$ (6)	O_2 (cfs) (7)

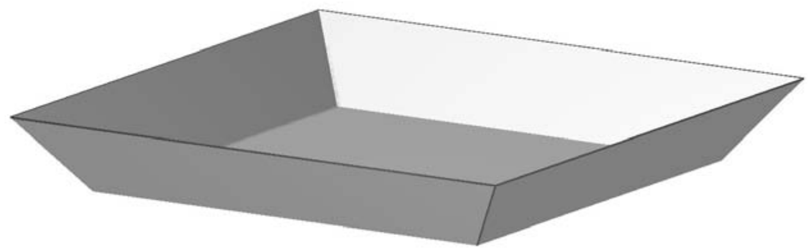
Table Number

Time (hrs) (1)	Inflow (cfs) (2)	$\frac{I_1 + I_2}{2}$ (3)	$\frac{S_1}{\Delta T} + \frac{0_1}{2}$ (4)	O_1 (cfs) (5)	$\frac{S_2}{\Delta T} + \frac{0_2}{2}$ (6)	O_2 (cfs) (7)
11.0	.76					
11.3	1.1	.093	0	0.0	.93	0.0
11.6	1.6	1.35	.93	0.0	2.28	0.11
11.9	4.5	3.1	2.28	0.11	5.27	0.19
12.0	8.9	6.7	5.27	0.19	11.8	0.42
12.1	17	12.95	11.8	0.42	24.3	0.94
12.2	25.7	21.35	24.3	0.94	44.7	2.52
12.3	25.7	25.7	44.7	2.52	67.9	3.89
12.4	17.4	21.6	67.9	3.89	85.6	4.84
12.5	10.6	14.0	85.6	4.84	94.8	5.37
12.6	7.4	9.0	94.8	5.37	98.4	5.47
12.7	5.5	6.45	98.4	5.47	99.4	5.49
12.8	4.3	4.90	99.4	5.49	98.8	5.47
13.0	3	3.65	98.8	5.47	97.0	5.43
13.2	2.5	2.75	97.0	5.43	94.3	5.33
13.4	2.2	2.35	94.3	5.33	91.3	5.16
13.6	1.9	2.10	91.3	5.16	88.2	5.03
13.8	1.8	1.85	88.2	5.03	85.02	4.95
14.0	1.7	1.75	85.02	4.95	81.82	5.40
14.3	1.0	1.35	81.82	4.50	78.67	4.40

Detention Example

50 year, 24hr storm





Given :

side slopes of pond = 4:1 = Z

depth = D = 3.5 feet, use 0.5 foot increments

dimensions of pond bottom = W = L = 122 feet

122 feet x 122 feet

For a trapezoidal basin:

Using equation : Volume = $LWD + (L + W)ZD^2 + 4/3Z^2D^3$

$\text{Volume}_{1.5\ \text{feet}} = (122)(122)(1.5) + (122+122)(4)(1.5)^2 + 4/3(4)^2(1.5)^3$

$\text{Volume}_{1.5\ \text{feet}} = 24594\ \text{ft}^3$